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THESIS

**MOVING PLATFORM SIMULATOR III:
AN ENHANCED HIGH-PERFORMANCE REAL-TIME
GRAPHICS SIMULATOR WITH MULTIPLE
RESOLUTION DISPLAY AND LIGHTING**

by

Curtis Paul Cheeseman

June 1990

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Computer Science Dept. Naval Postgraduate School 6b. OFFICE SYMBOL (if applicable) 52	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000	7b. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
MOVING PLATFORM SIMULATOR III: AN ENHANCED HIGH-PERFORMANCE REAL-TIME GRAPHICS SIMULATOR WITH MULTIPLE RESOLUTION DISPLAY AND LIGHTING

12. PERSONAL AUTHOR(S)
Cheeseman, Curtis P.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Master's Thesis	FROM TO	June 1990	56

16. SUPPLEMENTARY NOTATION
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Moving Platform Simulators, Visual Simulators, Real-Time Graphics

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This ~~study~~ Thesis is a continuation of previous work conducted in the development of low cost real-time Moving Platform Simulators using three-dimensional digital terrain elevation data and a high-performance Silicon Graphics, Inc., IRIS 4D/120GTX graphics workstation. Most notably this effort combines work conducted on previous models to display high-resolution terrain in multiple interval resolutions using either polygon or mesh drawing algorithms. In addition to the simulator's capability to display the special high-resolution terrain data provided by the United States Army Test and Experimentation Command (USATEC) it also supports Defense Mapping Agency (DMA) Level 1 Digital Terrain Elevation Data (DTED). Further work was performed enhancing user interfaces and visual displays. This paper describes the simulator, Moving Platform Simulator III (MPS III), listing its enhancements and features.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT. [ ] DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Prof. Michael J. Zyda	22b. TELEPHONE (Include Area Code) (408) 646-2305 22c. OFFICE SYMBOL Code CS/Zk

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

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MOVING PLATFORM SIMULATOR III: AN ENHANCED HIGH-PERFORMANCE REAL-TIME GRAPHICS SIMULATOR WITH MULTIPLE RESOLUTION DISPLAY AND LIGHTING

by

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
June 1990

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ABSTRACT

This study is a continuation of previous work conducted in the development of low cost real-time Moving Platform Simulators using three-dimensional digital terrain elevation data and a high-performance Silicon Graphics, Inc., IRIS 4D/120GTX graphics workstation. Most notably this effort combines work conducted on previous models to develop a single comprehensive simulator that demonstrates the most desirable features of those models. Integrated in the development of this simulator is the ability to display high-resolution terrain in multiple interval resolutions using either polygon or mesh drawing algorithms. In addition to the simulator's capability to display the special high-resolution terrain data provided by the United States Army Test and Experimentation Command (USATEC) it also supports Defense Mapping Agency (DMA) Level 1 Digital Terrain Elevation Data (DTED). Further work was performed enhancing user interfaces and visual displays. This paper describes the simulator, Moving Platform Simulator III (MPS III), listing its enhancements and features.

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I. INTRODUCTION

A. BACKGROUND

Previous research at the Naval Postgraduate School has resulted in the development of two real-time Moving Platform Simulators, Moving Platform Simulator (MPS) [Ref. 1] and Moving Platform Simulator II (MPS II) [Ref. 2]. Both simulators were developed on the Silicon Graphics, Inc., IRIS 4D/70GT high-performance graphics workstation. The first moving platform simulator, MPS, was developed to establish a benchmark from which to evaluate further research in the area of real-time three-dimensional graphics simulations. The simulator provided three-dimensional terrain simulation along with moving platforms (jeeps, trucks, tanks, and missiles) that maneuvered over the digital terrain. The development of MPS II was motivated by requirements established by the United States Army Test and Experimentation Command (USATEC), Fort Ord, California, for use in evaluating new weapons systems for use by the US Armed Forces. USATEC conducts most of its major experiments at Fort Hunter-Liggett (FHL), California. The primary purpose of MPS II was to provide USATEC with a simulator that could graphically display moving platforms on realistic high-resolution terrain in real-time with no artificial boundaries placed on the movement of vehicles about the terrain. The detailed terrain database of FHL was provided by USATEC for this research. To accomplish this task MPS had to be enhanced in many areas to improve the graphics display performance and realism requested by USATEC. Additionally, USATEC

requested that selected intervisibility (line-of-sight) computations between designated positions be displayed in a two-dimensional graphical display at the completion of any segment of an exercise [Ref. 2]. Thus MPS II was developed to enhance MPS's capabilities to better suit the specific needs of USATEC, while at the same time continuing the research into the graphics capabilities of high-performance graphics workstations as they pertain to real-time applications.

B. REQUIRED ENHANCEMENTS

Due to the successes of MPS, MPS II, and other programs that have been derived from them, it was decided that a new moving platform simulator should be developed that incorporated features or enhancements from both of them. The reason for this decision was that both programs contained specific features that would be desirable in all future derivatives of these systems. For example MPS II has the capability of using only the special terrain data set of FHL provided by USATEC while MPS also has the ability to display three-dimensional terrain from Defense Mapping Agency (DMA) Level 1 Digital Terrain Elevation Data (DTED). Additionally, having a system that supports both polygon drawing and the enhanced mesh drawing algorithms of MPS and MPS II respectively is highly desirable. Work on other three-dimensional real-time graphics systems, Command and Control Workstation of the Future (CCWF) [Ref. 3] and Forward Observer Simulator Trainer (FOST) [Ref. 4], at the Naval Postgraduate School (NPS) has also introduced improved drawing algorithms and user interfaces that have demonstrated improved graphics workstation performance and user friendliness. The consolidation of

these programs will also provide a simulator that will lend itself to further performance testing as future upgrades of system hardware are implemented. In regards to system hardware upgrades, research is now being conducted on methods of reading three-dimensional terrain data and computationally processing the terrain normals using the multiple processor capabilities of the Silicon Graphics, Inc., IRIS 4D/120GTX graphics workstation. As further hardware changes are made; increased number of CPUs, added memory, improved system hardware modifications, the Moving Platform Simulator III system will provide a sound basis for future enhancement, graphical workstation performance measurement, and possible SIMNET integration.

II. BACKGROUND AND SIMULATOR DEVELOPMENT HISTORY

The Moving Platform Simulator III (MPS III) has evolved from a number of student research projects at the Naval Postgraduate School. As continued progress is made in the advancement of relatively inexpensive high performance graphics workstations, it has become more feasible to develop graphics simulators to perform realistic real-time simulations involving moving platforms. However, as simulator realism increases workstation performance suffers degradation. Therefore, to obtain a real-time simulator that functions satisfactorily, realism must be sacrificed to allow the graphics workstation to achieve acceptable levels of performance. The development of MPS III is consistent with the realism/performance trade-off development approach in that it allows users the option to invoke various workstation capabilities from which detailed workstation performance characteristics can be measured. To get a better understanding of the capabilities of MPS III, we must look at the other systems developed at NPS from which it has evolved.

A. THE MOVING PLATFORM SIMULATOR (MPS)

The Moving Platform Simulator (MPS) is a real-time graphics simulator that allows the user to display multiple moving platforms driving on or flying over actual three-dimensional terrain data in normal or network mode. The polygon drawing algorithm used to display the terrain uses eight primary colors and eight secondary colors to create

a checkerboarding effect which gives the terrain additional relief and depth when areas of similar elevation are traversed. By making slight adjustments to the dial interface the user has the ability to alter the parameters of the lighting model creating scenario changes that add additional realism and special effects to the simulator. MPS was developed on a Silicon Graphics, Inc., IRIS 4D/70GT high-performance graphics workstation. Some of the primary features included in MPS are the following:

- Entire compatibility with the 4Sight [Ref. 5] window management system.
- Selectable ten square kilometer operation area from a 35 square kilometer database.
- Selectable multicolored terrain elevation color schemes.
- Realistic lighting model that includes user selected month and hour to control the sun's location and intensity.
- A terrain drawing algorithm that utilizes distance attenuation to enhance performance.
- Hidden surface removal using z-buffering.
- FOGM's ability to track and destroy land vehicles.
- Broadcast networking support simultaneous multi-workstation simulations.

MPS also has the capability to display user selected detailed terrain from DMA Level 1 DTED data files and the special terrain data sample of FHL provided by USATEC. [Ref. 1]

B. MOVING PLATFORM SIMULATOR II (MPS II)

The Moving Platform Simulator II (MPS II) is an enhancement of MPS's capabilities to better facilitate the needs of USATEC, in conjunction with ongoing research to test the performance capabilities of high-performance graphics workstations as they apply to real-time applications. Therefore, there are many similarities between the two application programs. Most enhancements made were either necessary to achieve desired simulator results or to examine specific topics of interest as requested by USATEC. MPS II has the capability to allow the user to operate multiple moving platforms over variable resolution intervals of the 12.5 meter interval high resolution terrain data of FHL in normal or network mode. The ability to vary the intervals of terrain resolution combined with the *mesh* drawing primitive significantly enhances the quality and realism of display. To compliment the smoothing effect of the *mesh* drawing primitive, ground vehicle dynamics were improved to dampen the effect of crossing polygon intersections. In an effort to further expand the realism of the simulator, MPS II models time by measuring elapsed time, using the CPU system clock as a reference. This allows the system to realistically update all vehicle positions via "dead-reckoning" while other events are taking place in the simulator. A list of enhancements made to the functionality of MPS include some of the following features:

- Improved drawing algorithms (Mesh) that provide more realistic looking terrain features.
- Display of high resolution terrain elevation data at 12.5, 25, 50, 75, and 100 meter intervals.

- Integration of real-time, actual platform data into the simulator to control the position and movements of displayed platforms.
- Presentation of distributed computing architecture to maximize display performance.
- Intervisibility determinations and display.
- Improved networking capabilities using the USATEC Visual Information Display System (VIDS) format.

MPS II's ability to display terrain in multiple intervals of resolution is a significant improvement in the development of real-time moving platform simulators at NPS. In addition to supporting the needs of USATEC, MPS II provides an excellent platform with which to evaluate the performance of the Silicon Graphics, Inc., IRIS 4D/70GT and the Silicon Graphics, Inc., IRIS 4D/120GTX and other workstations in the application program environment. [Ref. 2]

C. SUMMARY

The three-dimensional real-time moving platform simulators developed at NPS have been created to evaluate system performance and to meet specific research requirements. However, even though they basically evolved from similar models, they are quite different. Therefore, to better examine the performance characteristics of the current hardware available, a need exists for a simulator that incorporates the most desirable features of the previous systems. For example, the polygon drawing algorithm which produces checkerboarded terrain in MPS would significantly enhance the visual landscape of the high resolution terrain in MPS II while moving platforms are crossing flat terrain.

Likewise, platform movement in MPS would be more realistic if it incorporated the ground vehicle dynamics and time model used in MPS II to update vehicle locations. A desirable system would include polygon and mesh drawing algorithms, time modeling, improved vehicle dynamics, variable resolution terrain display, and the ability to access both DMA Level 1 DTED data and the special terrain data base of FHL provided by USATEC. Additionally, one high performance real-time application that incorporated the best features of the previous systems would provide a robust moving platform simulator from which to base further development and performance testing.

III. MOVING PLATFORM SIMULATOR III DESCRIPTION

A. SYSTEM OVERVIEW

The Moving Platform Simulator III (MPS III) is a high-resolution real-time graphics simulator that models platform ground movement and flight over multiple-resolution three-dimensional terrain. MPS III is an enhancement of previous moving platform simulators developed at NPS to incorporate the most desired features of those systems. Therefore, the MPS III simulator may seem very similar to its predecessors, however, the functionality and potential of this system provide a more robust foundation from which to pursue research into the capabilities of high-performance graphics workstations. Due to the modularity of MPS III's design it can easily be modified for future system upgrades or integration into other research applications.

B. SIMULATOR CONSOLIDATION NEEDED

Ongoing research in the development and implementation of high-performance real-time graphics applications at NPS has produced many diverse systems that each highlight one or a combination of the many advanced features of the Silicon Graphics, Inc., IRIS graphics workstations being utilized. To acquire a better understanding of these features (Gouraud shading, Lighting, Overlays, Double Buffering, Z-Buffering, etc., [Ref. 6]) and their effects on system performance as related to the current applications available it was

determined that a simulator that consolidated the most desirable features would be warranted.

The initial concern was that the system had to be able to access and display DMA Level 1 DTED data and the special high-resolution data of FHL provided by USATEC. There also could be no constraints placed upon the degree of resolution displayed during two and three-dimensional operation.

Secondly, the moving platform simulator had to have the capability of displaying three-dimensional multiple-resolution terrain using either polygon or mesh mode drawing algorithms. To accomplish this task, terrain drawing algorithms needed to be developed or modified from previous applications. The primary purpose of this requirement was to take advantage of the checkerboarding effect produced by the polygon drawing algorithm, versus the smooth terrain features of mesh mode drawing, to add relief and depth while navigating platforms over terrain of similar elevation. Consideration was also given to the fact that system display performance could be more reliably evaluated if all test operations were conducted and demonstrated by one application program.

Also, deemed essential to this moving platform simulator was the ability to model real time and have network capabilities. Other revisions to user interfaces and displays would be devised to improve characteristics or correct deficiencies as required.

C. SYSTEM FEATURES

The Moving Platform Simulator III (MPS III) simulator takes advantage of the development and research conducted on several moving platform simulators at NPS, most

notably the MPS and MPS II. The basic platform simulator used as a foundation to build MPS III, was MPS II. MPS III was developed on a Silicon Graphics, Inc., IRIS 4D/120GTX high-performance graphics workstation. Some of the additional capabilities of the Moving Platform Simulator III include:

- An improved mesh drawing algorithm that provides more realistic looking terrain and water.
- An improved polygon drawing algorithm that provides checkerboarded terrain.
- Display of high resolution terrain at 12.5 (mesh only), 25, 50, 75, and 100 meter intervals using polygon or mesh drawing algorithms.
- The ability to dynamically access standard DMA Level 1 DTED data files or the special high-resolution terrain data of FHL.
- All features and displays integrated into one graphics workstation.
- Improved functionality of user interfaces.

Other modifications were made to the application program to employ software engineering principles that improved modularity of design and simplified program code.

IV. DIGITAL TERRAIN DATABASES

The MPS III simulator was designed to display DMA Level 1 DTED terrain data files and the special high-resolution DMA terrain data of FHL. The simulator is capable of displaying the three-dimensional terrain data in real-time or while networking with other graphics workstations.

A. STANDARD DMA LEVEL 1 DTED DATA FILES

Each of the standard DMA Level 1 DTED data files used in the MPS III are the same databases used in CCWF and FOST [Refs. 3 and 4]. Each database file consists of 1201 by 1201 sixteen bit integer height values which cover an area of sixty by sixty square nautical miles. The file name and coordinates of the lower left hand corner of the file are located in a header file associated with each terrain area. For example, the file 30N130E has a lower left hand coordinate of 30 degrees north and 130 degrees east. The terrain data points of the file are approximately 100 meters or 3 seconds apart.

B. FORT HUNTER-LIGGETT DATABASE

The special DMA digital terrain elevation database (DTED) file of Fort Hunter-Liggett (FHL), California was provided to NPS by USATEC in support of ongoing research that USATEC wants conducted. The database represents a 36 kilometer by 35 kilometer area of FHL, consisting of elevation and vegetation data points in 12.5 meter increments. Each data point contains 16 bits. The three most significant bits are

vegetation code, which the simulator ignores, and the remaining 13 bits represent the elevation of the point measured in feet. The Moving Platform Simulator III has the capability of displaying the 36 kilometer by 35 kilometer database area, approximately 16,128,000 bytes, with a resolution of 12.5 meters. Thus, the resolution of the terrain displayed while using the FHL database can be up to eight times that of a standard DMA Level 1 DTED data file.

C. DATABASE ACCESS

1. Methodology

Because the special high-resolution database of FHL and the DMA Level 1 DTED data files are structured differently, it was determined that separate functions controlled by a switch statement should be used to access the database files. By using two separate functions to read the data, the procedures could be established to access data faster and in a simpler manner. To accomplish this task in MPS III, a similar procedure developed for use in FOST [Ref. 4] was modified to access both the standard DMA Level 1 DTED data files and the special high-resolution database of FHL. The code which accomplishes these procedures is located in the file *display_big_map.c*.

2. Database Reads

Whenever a new database is designated for an area of operation, either at simulator start up or during normal execution, the entire data file is read into the simulator. If the simulator is accessing the high-resolution FHL data file, only every eighth point (100 meter resolution) is retained in a two-dimensional array for displaying

the initial two-dimensional 35 kilometer by 35 kilometer terrain map. Once a ten square kilometer area of operation is selected from either the of the database types, there is a subsequent read made to restructure the data into a two-dimensional array that saves the highest total of resolution data points available for any given database file. Whenever database information is being read from the disk, a display message and wait bar are flashed to the screen to indicate the read status and progress.

3. DMA Level 1 DTED Database Access Algorithms

a. Initial Database Read

After a terrain database selection is made from the popup menu, the initial database read occurs. The first thing done is a check to ensure that the DTED file has the correct dimensions, 1201 by 1201, to work in the simulator. After successful completion of this test, the algorithm in Figure 4.1 is performed to execute the read.

The routine used to read the DTED database is simpler than the algorithm used to read the high-resolution terrain of FHL. The data is read column by column until the entire data file is accessed. Since all DMA Level 1 DTED files are accessed after the initial display of the FHL terrain map, the new data read overwrites the previous database data stored in the two-dimensional *data* array.

b. Subsequent Database Reads

Subsequent database reads are conducted after a ten kilometer area has been selected by the user. The segment of the procedure shown in Figure 4.2 for the data read is located in the file *read_data.c*. This data read procedure is very similar to the

```
display_DMA_map()
{
  short  data[1201][1201];
  char   str[100];
  int    fd;
  short  col;

  fd = open(str,RD);  /* Open data file for read */
  /* Bypass the header in the DMA data file */
  lseek(fd,3348,0);
  for(col = 0; col < 1201; ++col)
  {
    /* Bypass recog sym and record header */
    lseek(fd,8,1);
    /* Read entire column */
    read(fd,&data[col][0],2402);
  }
}
```

Figure 4.1 Initial DMA Level 1 DTED Database Read

initial read operation used above except an offset must be calculated to get to the correct place in the data file. The data points are then stored in the *dted* array for later display and drawing routines to use.

4. FHL Database Access Algorithms

a. Initial Database Read

Upon start and initialization of the MPS III simulator, the first database accessed is the FHL database. The FHL database can also be accessed by selection from the main popup menu. The routine *display_fort_hunter_liggett_map* used to accomplish the read of the data is a modified version of the routine *display_big_map* used in MPS

```
read_data_DMA(filesource)
{
  short dted[801][801]; /* Large enough to hold 12.5 meter resolution */
  short x_grid_DMA, y_grid_DMA;
  int   fd;
  short row, col;
  char  path[100];

  strcat(path,current_DMA_filename);
  if((fd = open(path,RD)) < 0)
  /* Process error code */

  /* Bypass the header in the data file */
  lseek(fd,3348,0);

  /* Calculate the offset to get to the correct location in the data
     file. The 8 is for recog sym and record header; 4 is for checksum
  */
  lseek(fd,(long)(x_grid_DMA*(8+2402+4) + (8+y_grid_DMA*2)),1);

  /* The standard DTED interval is approximately 100 meters */
  for (col=0; col<100; col++)
  {
     read(fd,&dted[col][0],200);
     lseek(fd,8 + 2202 + 4,1);
  }
  close(fd);
}
```

Figure 4.2 Ten Square Kilometer DMA Database Read

II [Ref. 2]. Because of the higher-resolution of the FHL database, a totally different initial read algorithm is executed. To demonstrate the difference between the two initial database reads a segment of the code is introduced in Figure 4.3.

```
display_fort_hunter_liggett_map()
{
   short  data[801][801];
   short  in_elev[BYTES_PER_COL];
   short  gridcol, gridrow, col, row;
   int    fd, count;

   fd = open(TERRAIN_DATAFILE,RD); /* Open data file to read */
   lseek(fd,0,0); /* Move file pointer to the beginning of file */

   for (gridcol = 0; gridcol < THIRTYFIVE_SQUARES; gridcol++)
   { /* Loop once for each column for 35 columns */
      count = 0;
      read(fd, &in_elev[0], BYTES_PER_COL); /* Read entire col, 1x35 Km */

      for (gridrow = 0; gridrow < THIRTYFIVE_SQUARES; gridrow++)
      /* Loop once for each of the 35 grid squares in the column. */

         /* Restructure the column of squares in a 2-D array */
         for (col = gridcol*PTS_PER_K;
                  col < (gridcol*PTS_PER_K) + PTS_PER_K; col++)
         {
            for (row = gridrow*PTS_PER_K;
                     row < (gridrow*PTS_PER_K) + PTS_PER_K; row++)
            {
               data[col][row] = in_elev[count];
               count += PTS_PER_HUNDRED; /* Increment count by 8. */
            }
            /* Increment counter to first point in next column. */
            count += PTS_BETWEEN_COL;
         }
      }
   }
}
```

Figure 4.3 Initial FHL Database Read

To take advantage of the structure of the high-resolution terrain database and to facilitate faster disk access, the data is read in 35 incremental blocks. One block for each kilometer of terrain data to be displayed. Once a block of terrain elevation data is read, it is temporarily stored in the *in_elev* array and then restructured to make up the data points of the two-dimensional *data* array. A more detailed discussion of this data access process is found in MPS II [Ref. 2].

b. Subsequent Database Reads

Database reads for the selected ten kilometer area of FHL are similar to the techniques used for subsequent database reads of standard DMA Level 1 DTED data. For a comparison of the procedure *read_data_fhl* located in the file *read_data.c* see Figure 4.4. Upon completion of the database read, the entire block of 12.5 meter high-resolution terrain elevation data is restructured and stored in the *dted* array for further manipulation and display.

5. Database Elevations

In MPS III, the minimum and maximum elevations for each terrain area accessed are calculated and saved when the terrain elevation data is being read. The elevation range is calculated and then divided into 16 groups for the high-resolution terrain of FHL and eight groups for standard DMA Level 1 DTED data. Each group is then assigned a different color to more accurately represent the elevation variations experienced across the selected terrain operation area. The technique used to determine the minimum and maximum elevations is the same as the one applied in MPS II [Ref. 2].

```
read_data_fhl()
{
  short  dted[801][801], in_elev[SIZE_COL];
  short  x_grid, y_grid, row, col, gridcol, gridrow, initx, initz;
  int    offset, fd, count;

  /* Open the file with the 12.5 meter data points in it */
  fd = open(TERRAIN_DATAFILE,RD);

  /* Calculate the lower left starting point in the file */
  initx = (x_grid - 410)/10;
  initz = (y_grid - 600)/10;

  /* Calculate the starting offset point. */
  offset = 2*((initx*PTS_PER_GRID*GRIDS_PER_COL) +
                              initz*PTS_PER_GRID));
  lseek(fd,offset,0);

  for (gridcol=0; gridcol < TEN_SQUARES; gridcol++)
  {
    count = 0;
    read(fd, &in_elev[0], SIZE_COL);

    for (gridrow=0; gridrow < TEN_SQUARES; gridrow++)
      for (col=gridcol*PTS_ON_SIDE;
          col<(gridcol*PTS_ON_SIDE)+PTS_ON_SIDE; col++)
        for (row=gridrow*PTS_ON_SIDE;
            row<(gridrow*PTS_ON_SIDE)+PTS_ON_SIDE; row++)
        {
          dted[col][row] = ((in_elev[count] & ELEV_MASK) *
                                  FEET_TO_METERS);
          count++;
        }
    lseek(fd,(25*PTS_PER_GRID*BYTES_PER_POINT,1);
  }
  close(fd);
}
```

Figure 4.4 Ten Square Kilometer FHL Database Read

As with MPS II, the different color schemes available remain the same as in the original MPS [Ref. 1].

V. TERRAIN DISPLAY OPERATIONS

All terrain displayed in the MPS III simulator is displayed in two parts. The first part being the two-dimensional displays of the large map representing the entire database area and the 10 kilometer by 10 kilometer area selected by the user for platform operations. The second part being the real-time three-dimensional display of moving platforms over actual terrain elevation data. There are two separate display functions used to display three-dimensional terrain in MPS III, *drawterrain* and *drawpolyterrain*. The *drawterrain* routine is a variation of the *mesh* drawing routine used in MPS II, and the *drawpolyterrain* routine is an adapted multiple-resolution version of the polygon drawing routine used in MPS. Two-dimensional displays are fairly simple and are briefly addressed. Three-dimensional terrain drawing functions are covered in detail later in this chapter.

A. TWO-DIMENSIONAL TERRAIN DISPLAYS

The two-dimensional display procedures used in MPS III function identically to the procedures used in MPS II [Ref. 2]. Slight modifications were made to the existing code and similar routines were added to handle the display of DMA Level 1 DTED data files. Both types of two-dimensional terrain maps, Figure 5.1 and 5.2, are drawn by column in an up and to the right manner starting from the lower left-hand corner. The terrain colors are determined by the color scheme selected and the individual color assigned to each terrain elevation point displayed. To facilitate terrain drawing all terrain data points with

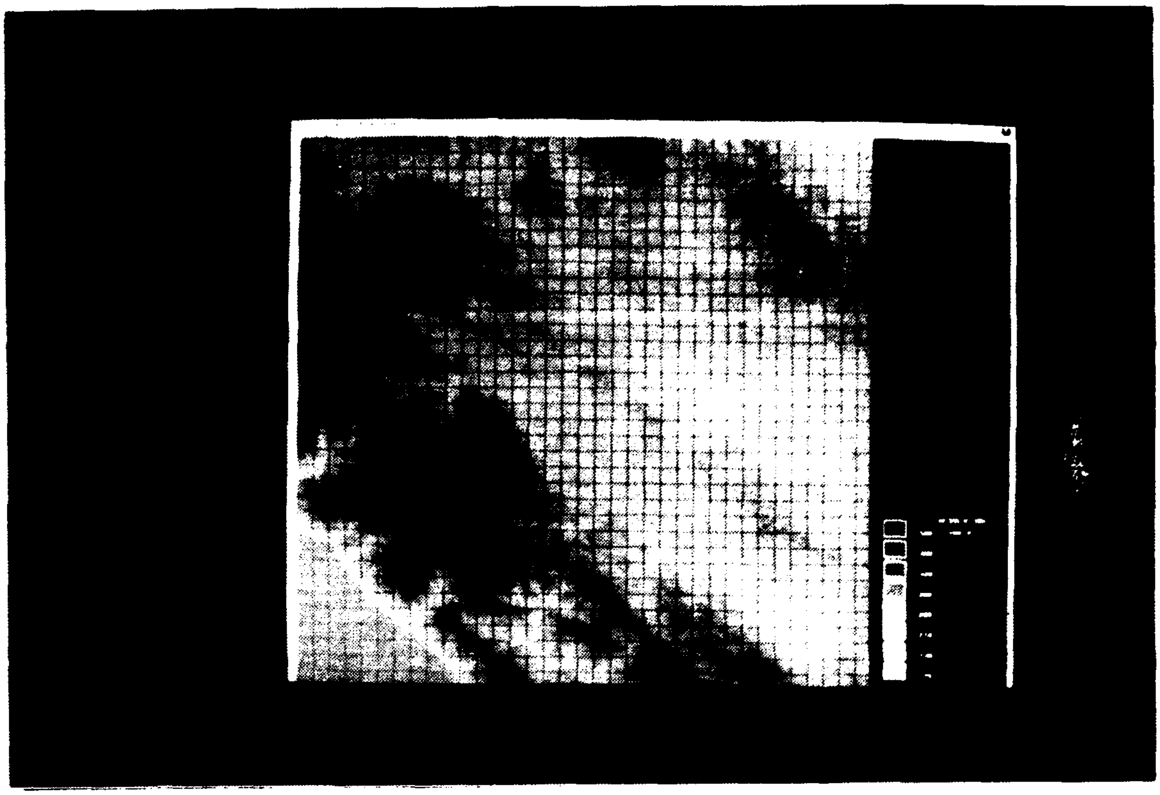

Figure 5.1 Two-dimensional Database Display

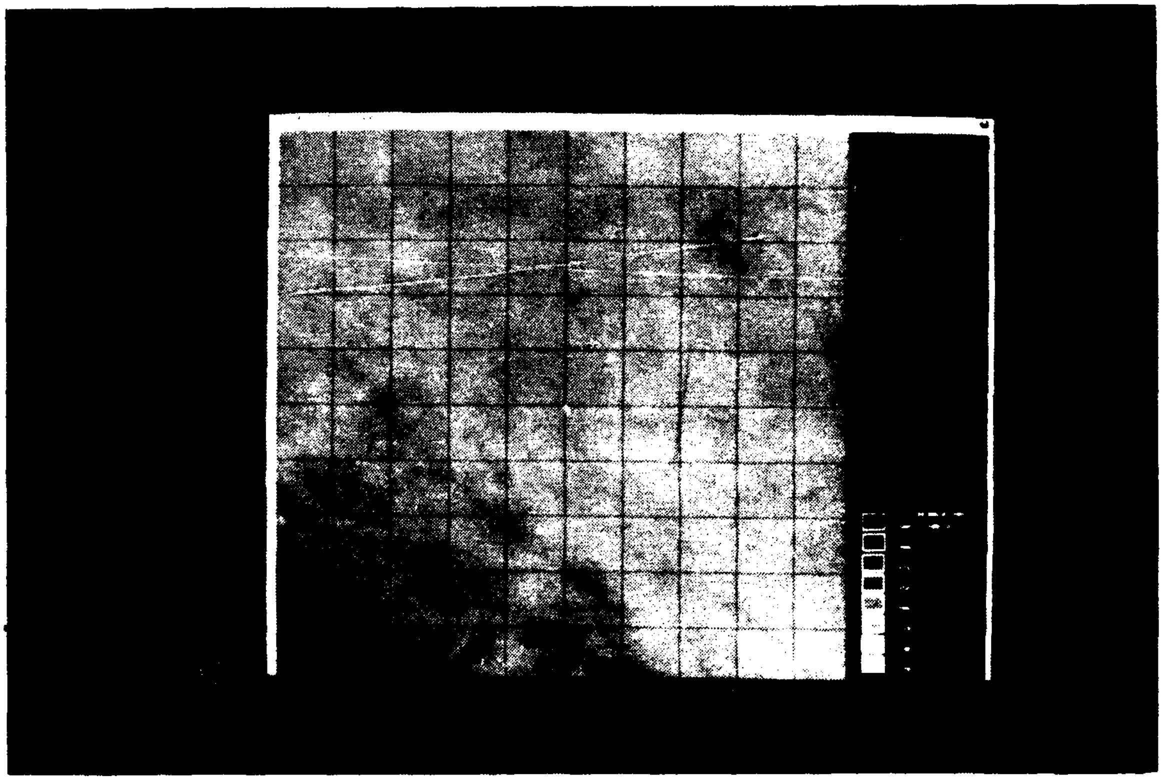

Figure 5.2 Two-dimensional 10 Km by 10 Km Display

an elevation equal to sea level are assumed to be water. No consideration is given to water above sea level. An elevation color scheme key is provided next to the map.

B. THREE-DIMENSIONAL TERRAIN DISPLAYS

1. Background

The first simulator to implement the complex three-dimensional terrain display algorithms being used in the current simulators at NPS was MPS [Ref. 1]. Subsequently, as ongoing research was conducted in the development of real-time moving platform simulators, the desire to display high-resolution terrain data in a more realistic manner led to further enhancements of the drawing algorithms used. MPS II was the first simulator to introduce multiple-resolution terrain drawing using the *mesh* primitive to display detailed high-resolution terrain [Ref. 2]. High-resolution terrain drawn using the *mesh* drawing algorithm significantly improves the clarity and realism of the terrain segment being displayed.

There are benefits to both methods of display. Even though terrain appears to be more realistic in MPS II, the smoothing effect caused by the implementation of the *mesh* routine introduces depth perception problems when expansive areas of flat terrain are encountered. This problem never occurs while traversing the checkerboarded terrain produced by the polygon drawing algorithm developed for MPS. The alternating colors of the grid squares produce a reference from which to establish distance and platform movement.

2. Polygon Drawing Algorithm

The terrain polygon drawing algorithm *drawpolyterrain* used in MPS III is an enhanced version of the *drawterrain* routine in MPS, adapted to display multiple-resolution terrain data to 25 meter resolution. Since CPU memory is less critical than when MPS was created, each drawing algorithm uses its own data structure. The data structure used in *drawpolyterrain* (see Figure 5.3) stores the entire area selected as triangles, using the x, y, and z coordinates of every vertex. By storing the entire data structure in memory the polygon drawing routine is easily toggled on and off with little

gridcoord[Z][X][2][3][3]

where: Z is the vertical index into the array.
X is the horizontal index into the array.
The last parameters represent the vertices
of the upper and lower triangles which make
up each 100 x 100 meter grid area.

Figure 5.3 Polygon Terrain Data Structure

delay experienced between three-dimensional terrain displays.

Terrain displayed using the polygon algorithm is constructed by drawing two adjacent triangles for each grid square. The checkerboarding effect is created by varying the colors of the alternating triangles. This drawing technique is efficient and fast. To further expedite the drawing process, terrain grid squares are made by dividing the look direction limits into three different groups; near, mid, and far (see Figure 5.4). This reduces the number of polygons drawn and minimizes system display degradation. The

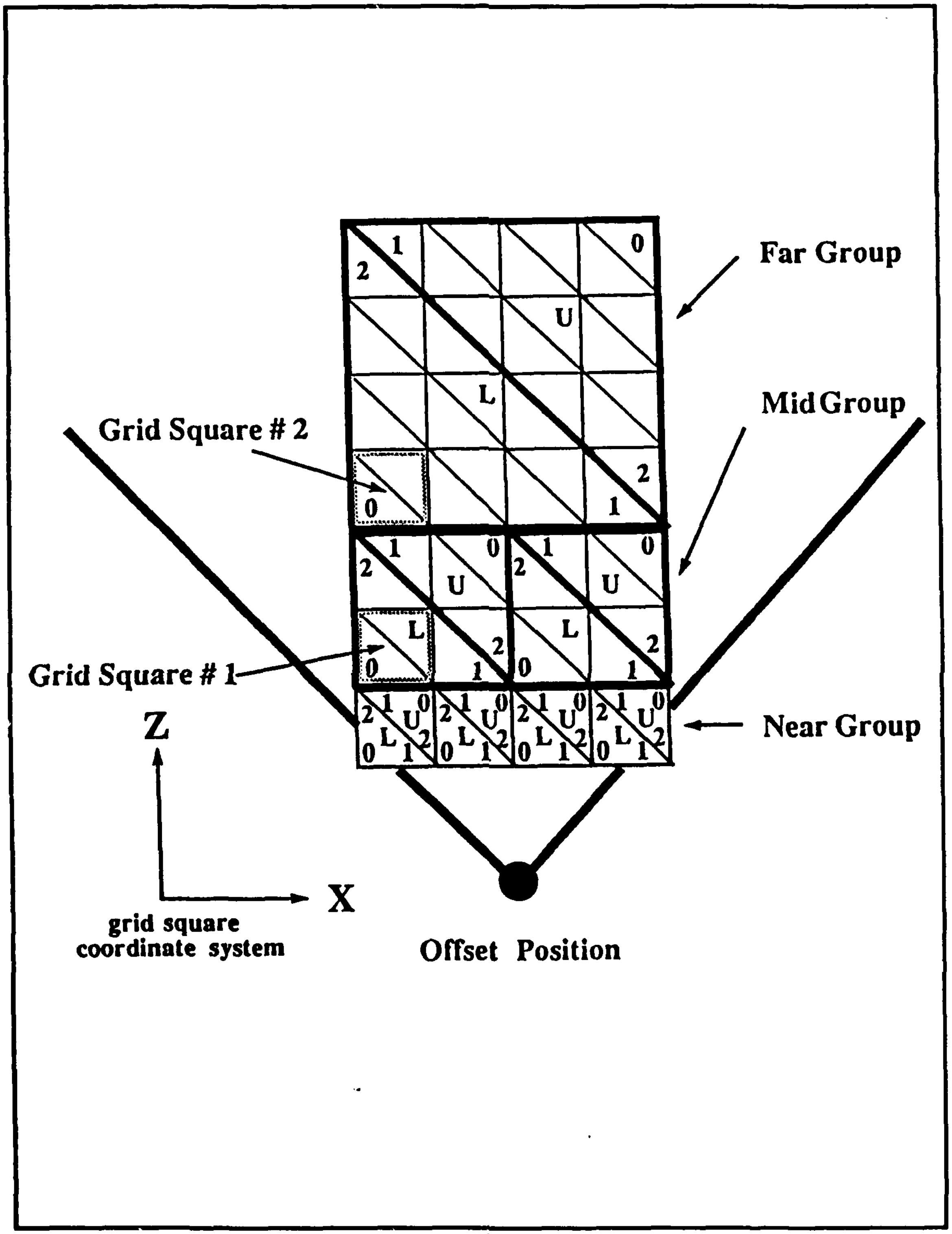

Figure 5.4 Polygon Terrain Construction

distance attenuation procedure used to make the determinations is discussed below. To develop a better understanding of the algorithm, a complete detailed explanation is given in [Ref. 1].

3. Mesh Drawing Algorithm

The *mesh* drawing algorithm used in MPS III is almost identical to the routine implemented in MPS II [Ref. 2]. The routine was slightly modified to incorporate a display loop used in FOST [Ref. 4] to more realistically display ocean elevations. Mesh mode drawing is the default drawing method for MPS III. The *mesh* algorithm itself is similar to the polygon algorithm addressed earlier. The main difference being the data structures used and the introduction of the *mesh* drawing primitive. The *mesh* primitive takes a series of vertices and draws a triangle [Ref. 6]. When subsequent vertices are received, they are connected to the previous vertices to form additional triangles. The routine is fast and makes efficient use of the much smaller *gridcoord2* data array, described in detail in [Ref. 2]. An additional advantage of the primitive is that it eliminates jagged edges between the intersection of two polygons and produces smooth surfaced displays.

4. Distance Attenuation

The distance attenuation algorithm used in the terrain drawing routines in MPS III is the same algorithm that is used by both MPS and MPS II [Refs. 1 and 2]. The algorithm reduces the system work load and increases real-time performance by reducing the number of polygons displayed in the field of view per display loop (see Figure 5.5).

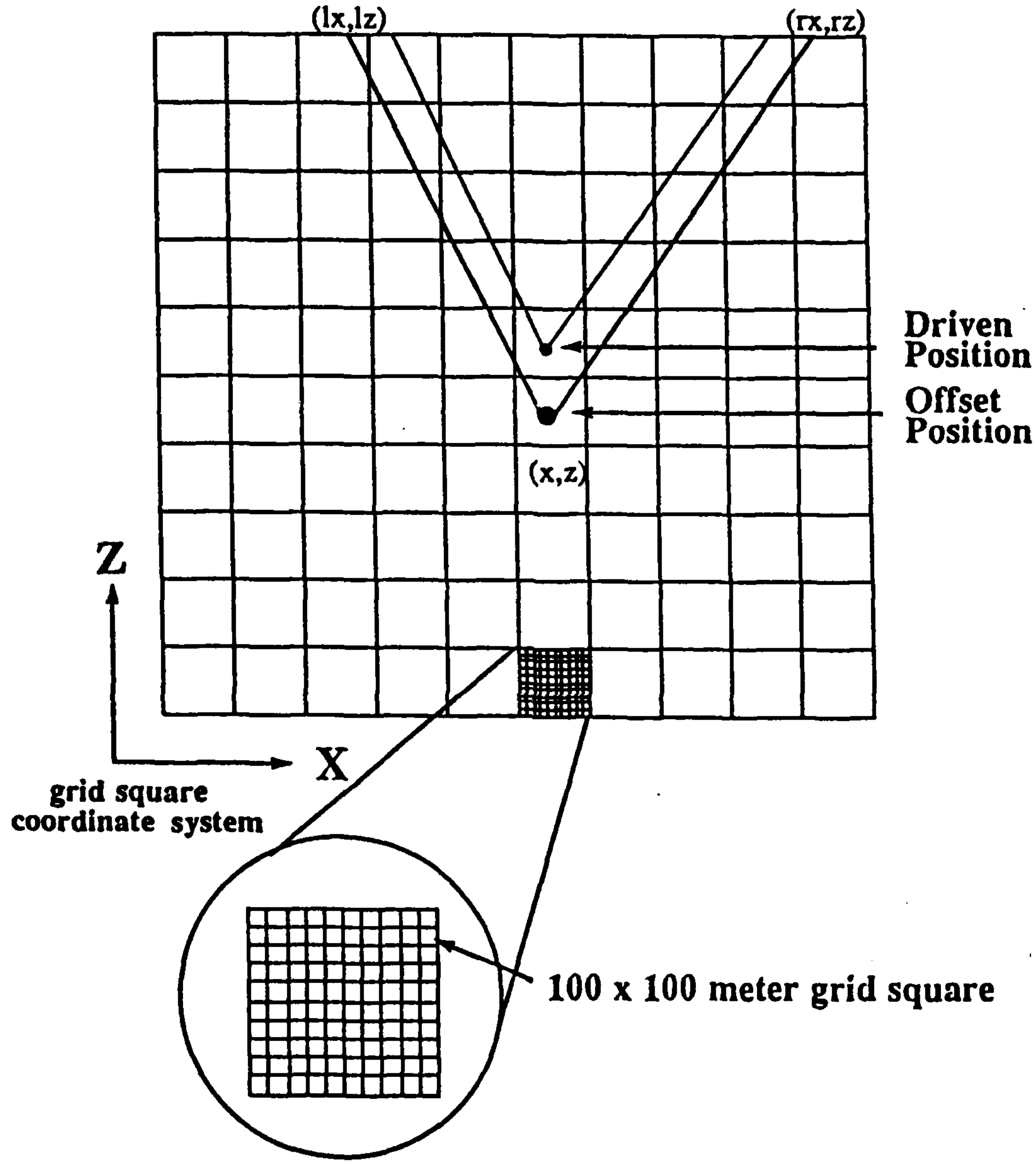

Figure 5.5 Field of View Display

This is accomplished by first calculating the field of view and then determining where the terrain boundaries are located. Once this has been done the viewing sector is divided into three groups based on distance. The three groups are then drawn with a resolution dependent upon their distance from the offset point (see Figure 5.6). The bottom line is that terrain at greater distances is drawn at lower resolutions.

5. Terrain Normals

In MPS III, the terrain normals for each drawing algorithm are precomputed and stored in separate arrays Even though this approach uses extensive amounts of main memory the technique is critical for real-time operations. The normals for each terrain drawing technique are computed in separate procedures. This facilitates computation of the different methods used and also provides modularity for future algorithm refinement.

The *drawpolyterrain* procedure uses polygon normals to depict the terrain colors and checkerboarding effect while the *drawterrain* procedure uses vertex normals. Vertex normals are calculated in MPS III by using either approximations or true vertex normals. The use of vertex normals simplifies data storage and provides for more realistic looking three-dimensional terrain. Comprehensive discussions of the types of data structures used and the methods implemented to perform these computations are contained in MPS and MPS II [Refs. 1 and 2].

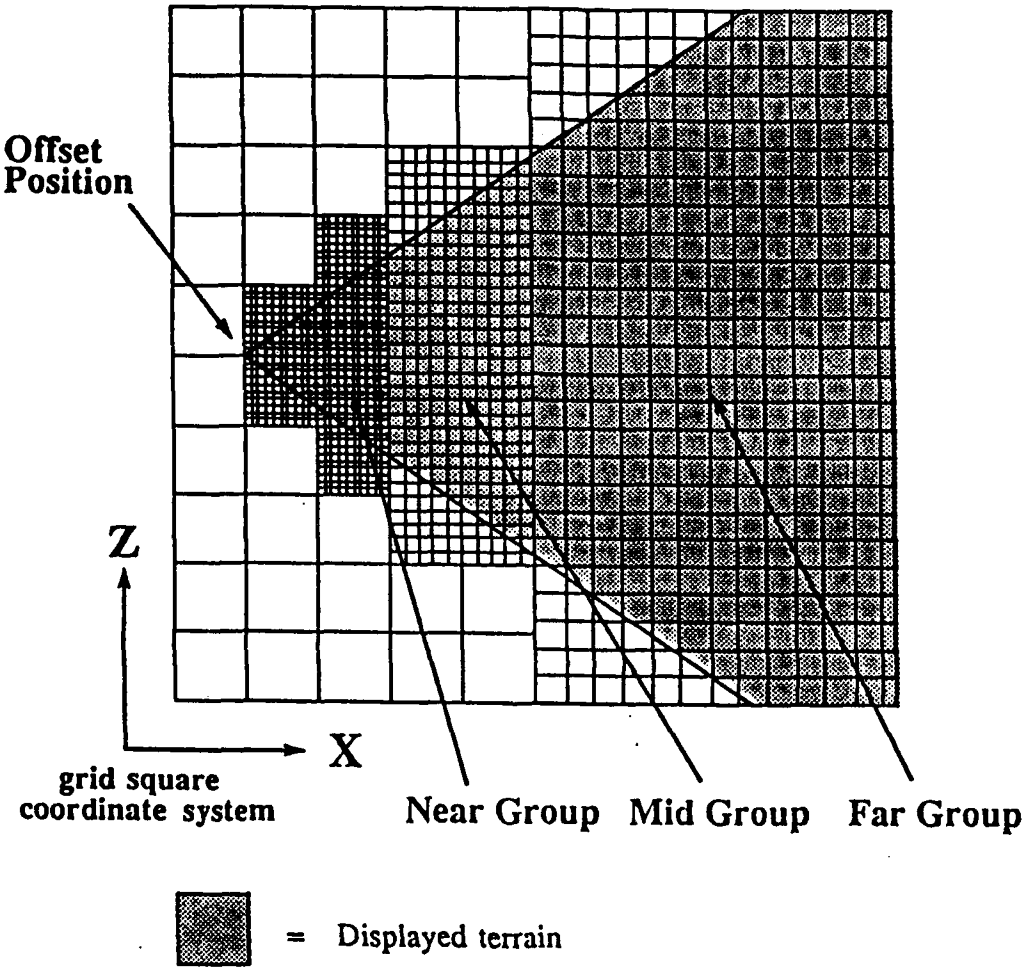

Figure 5.6 Distance Attenuation Example

VI. SYSTEM EVALUATION

A. PERFORMANCE MEASUREMENTS

In addition to developing a moving platform simulator that embodied the most desired features of previous work conducted at NPS, a supplementary objective of the work was to evaluate the performance characteristics of the Silicon Graphics, Inc., IRIS 4D/120GTX high-performance graphics workstation while displaying high-resolution three-dimensional terrain. Since no previous simulator has the ability to dynamically switch drawing routines "on the fly" while displaying multiple-resolution terrain, the performance results should more accurately represent performance comparisons under similar test scenarios. The performance results from research conducted on MPS II were used as a benchmark for comparison (see Table 6.1), because MPS II was the first simulator developed to display high-resolution terrain. The tests were conducted in accordance with procedures established for testing MPS [Ref. 1].

Testing for MPS III was performed in two phases. The first phase of testing evaluated MPS III drawing multiple-resolution checkerboarded terrain using the *drawpolyterrain* procedure. The second phase of testing utilized the *drawterrain* procedure featuring the *mesh* drawing primitive. Like previous testing, the primary focuses of concern are frames per second and polygons per second drawn. As the test results indicate, MPS III pushes the hardware to its extreme limits while displaying terrain above the 50 meter resolution level.

TABLE 6.1 MPS II PERFORMANCE DRAWING HIGH RESOLUTION TERRAIN ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	971	11.53	11195
75	ONE	55	1136	9.30	10564
50	ONE	55	3031	5.10	15458
25	ONE	55	11209	1.60	17934
12.5	ONE	55	42088	0.46	19360

DISPLAYING DETAILED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	3912	3.82	14943
75	ONE	55	6856	2.36	16180
50	ONE	55	15482	1.15	17804
25	ONE	55	61648	0.31	19110
12.5	ONE	55	246086	0.08	19686

1. Performance Test Conditions

To start the test **GO TO MAIN MENU** is selected from the main popup menu. This selects the default 10 kilometer by 10 kilometer operations area of the 35 kilometer by 35 kilometer database map of FHL. An open jeep platform, facing north in a stationary position, is placed in block (6,5) near the center of the two-dimensional operations map. Three-dimensional operations are started and test results are compiled.

After each test is conducted and recorded, the next level of terrain resolution is selected from the popup menu and the test is conducted again with a higher resolution display. The process is continued until all available three-dimensional terrain resolution options are exhausted. Similar test procedures are used for gathering the test results of both checkerboarded and non-checkerboarded three-dimensional terrain, using the *drawpolyterrain* and *drawterrain* routines respectively. No comparison information is available for checkerboarded terrain drawn at 12.5 meter resolution, because MPS III does not provide that feature.

2. Checkerboarded Terrain Drawing Performance

The ability to toggle between checkerboarded and non-checkerboarded high-resolution three-dimensional terrain in MPS III has significantly enhanced the capabilities of moving platform simulators at NPS. Even though terrain detail and realism are sacrificed (see Figures 6.1 and 6.2), the benefits gained by checkerboarding are justifiable when moving platforms are traversing expansive areas of flat terrain. The platform operator realizes the perception of depth and relief, with little system degradation as we see below.

As the results of Table 6.2 indicate, the performance of MPS III diminishes slightly while drawing high-resolution checkerboarded terrain using the polygon drawing algorithm of procedure *drawpolyterrain*. However, even though the performance of the system is slower, it is still capable of drawing acceptable real-time three-dimensional terrain at 50 meter resolution. An important result noticed is that when displaying higher resolution terrain, the gap in display performance becomes smaller between the two

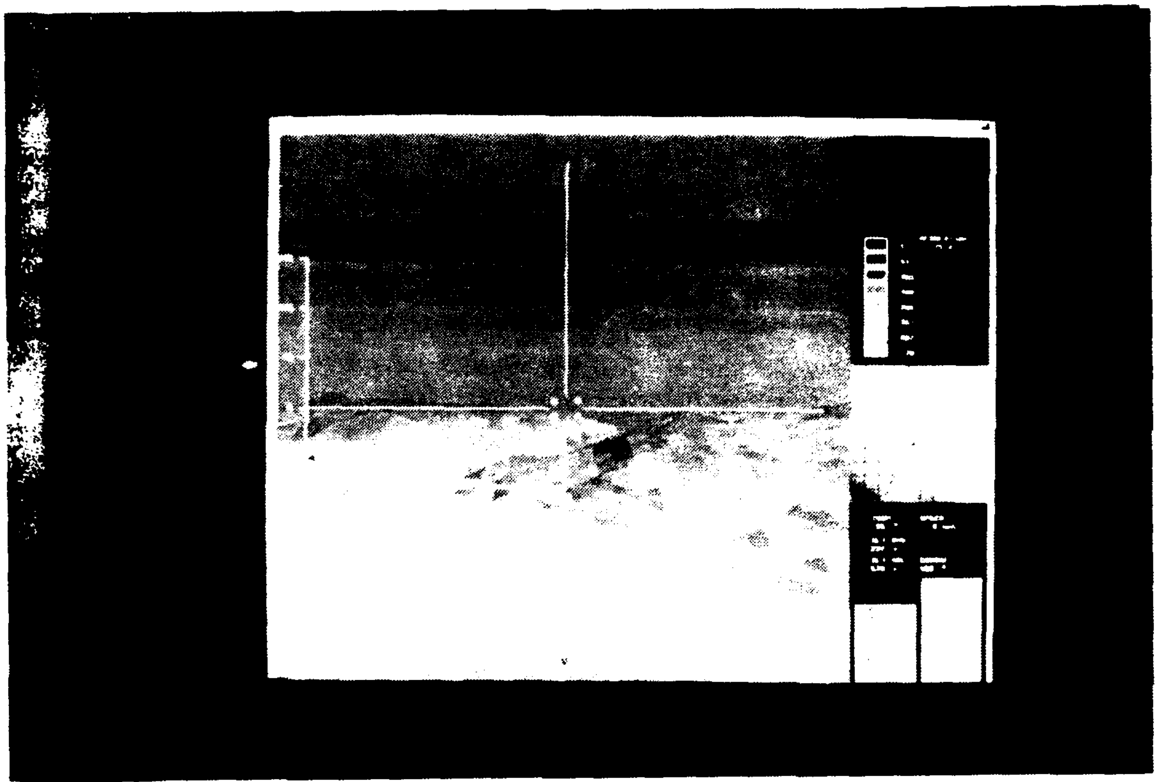

Figure 6.1 Checkerboarded Display Using 25 Meter Resolution

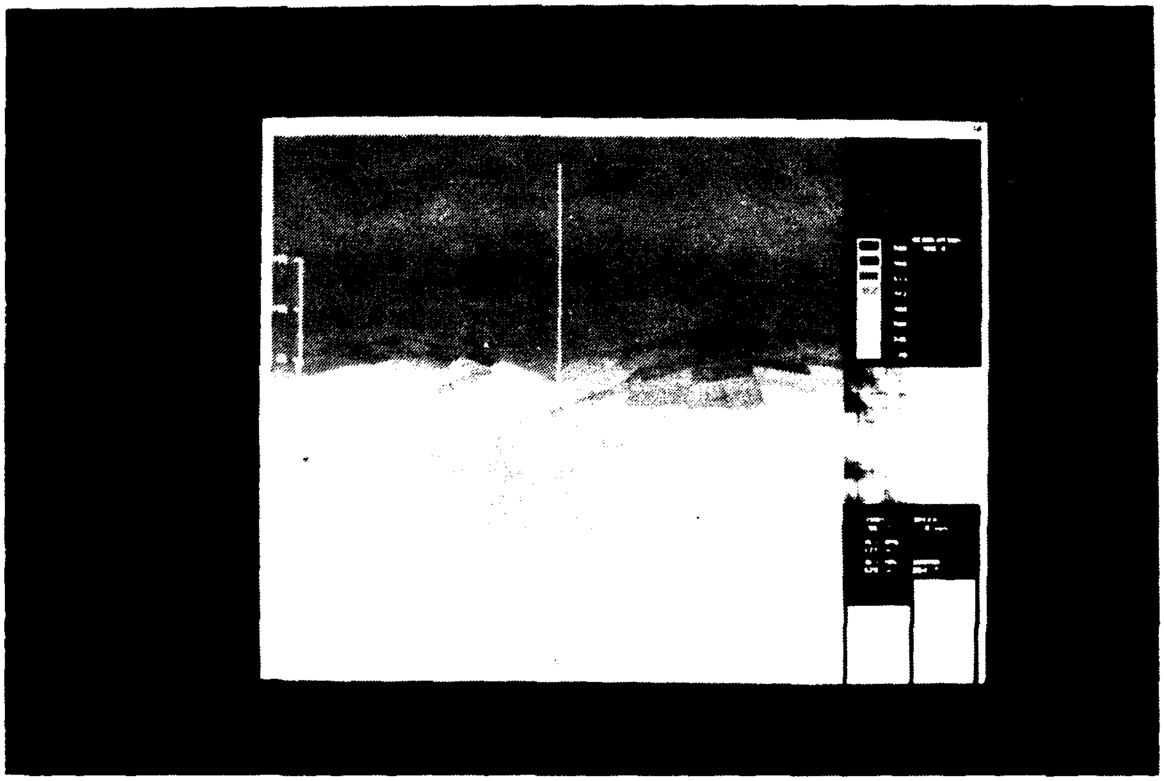

Figure 6.2 Checkerboarded Display Using 100 Meter Resolution

TABLE 6.2 MPS III PERFORMANCE DRAWING HIGH RESOLUTION POLYGON TERRAIN ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	935	7.10	6639
75	ONE	55	1222	5.54	6770
50	ONE	55	3038	2.74	8324
25	ONE	55	11051	0.83	9172

DISPLAYING DETAILED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	3839	2.31	8868
75	ONE	55	6739	1.35	9098
50	ONE	55	15217	0.63	9587
25	ONE	55	60601	0.16	9696

terrain drawing routines. This occurs because smaller polygons are drawn as terrain resolution increases. As the polygons keep getting smaller and smaller, the display rate performance gains of using the *mesh* drawing primitive are negligible.

3. Mesh Terrain Drawing Performance

Similar to previous test results accumulated during testing of MPS II [Ref. 2], the algorithm featuring the *mesh* drawing primitive was the superior performer. The

results of the evaluations conducted using the *drawterrain* procedure and *mesh* drawing primitive of MPS III are in Table 6.3.

TABLE 6.3 MPS III PERFORMANCE DRAWING HIGH RESOLUTION MESH TERRAIN ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	935	11.26	10528
75	ONE	55	1222	8.20	10020
50	ONE	55	3038	4.35	13215
25	ONE	55	11051	1.41	15581
12.5	ONE	55	41777	0.44	18381

DISPLAYING DETAILED TERRAIN

RESOLUTION	PLATFORMS	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND	POLYGONS PER SECOND
100	ONE	55	3841	3.47	13328
75	ONE	55	6741	2.21	14898
50	ONE	55	15219	1.02	15523
25	ONE	55	60603	0.34	20605
12.5	ONE	55	243827	0.08	19506

As mentioned previously, there is a slight performance increase when measured against the outcomes of terrain drawn using the *drawpolyterrain* procedure and polygon drawing algorithm. However, there is little comparison between the realism and quality of the terrain portrayed. The *mesh* drawing primitive smooths over polygon intersection points and creates almost lifelike terrain, especially when using 12.5 meter resolution data points and proper lighting techniques. Even the 25 meter resolution terrain shown in Figure 6.3 is a significant improvement over the quality of 100 meter resolution terrain in Figure 6.4.

B. PERFORMANCE LIMITATIONS

The most important performance hindrance is the system's inability to draw high-resolution terrain of resolution greater than 50 meters in real-time. The slow display rates cause platforms to unrealistically surge ahead as frames are drawn. Although, dial control and mouse mechanics were improved in MPS III, many of the problems associated with them still exist when the display rate falls below one frame per second. For example, sensitivity and responsiveness become totally inadequate for real-time operations. This problem should be solved when the Silicon Graphics, Inc., VGX upgrade is made to the existing hardware. The VGX upgrade has the advertised capability to render nearly 10 times as many polygons per second as the currently configured workstation. Therefore, modifications to procedures should not have to be made to correct the controls responsiveness problems. Performance measurements for each of the simulators running

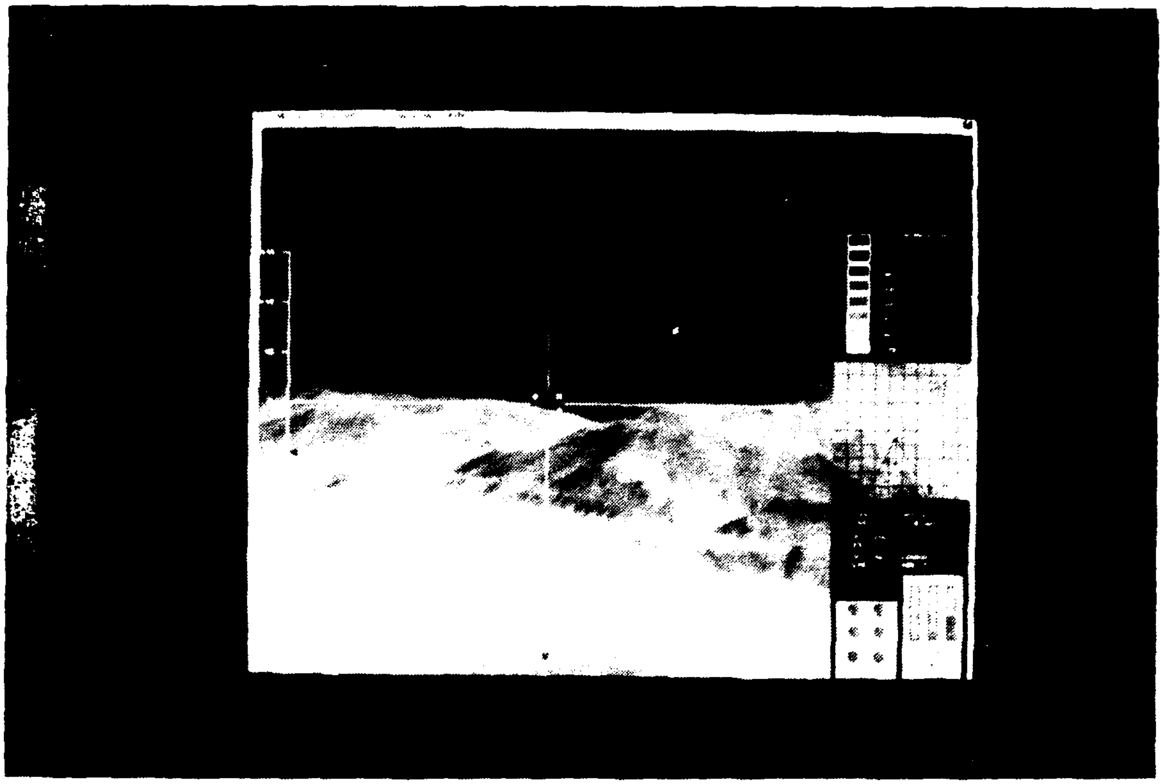

Figure 6.3 Mesh Display Using 25 Meter Resolution

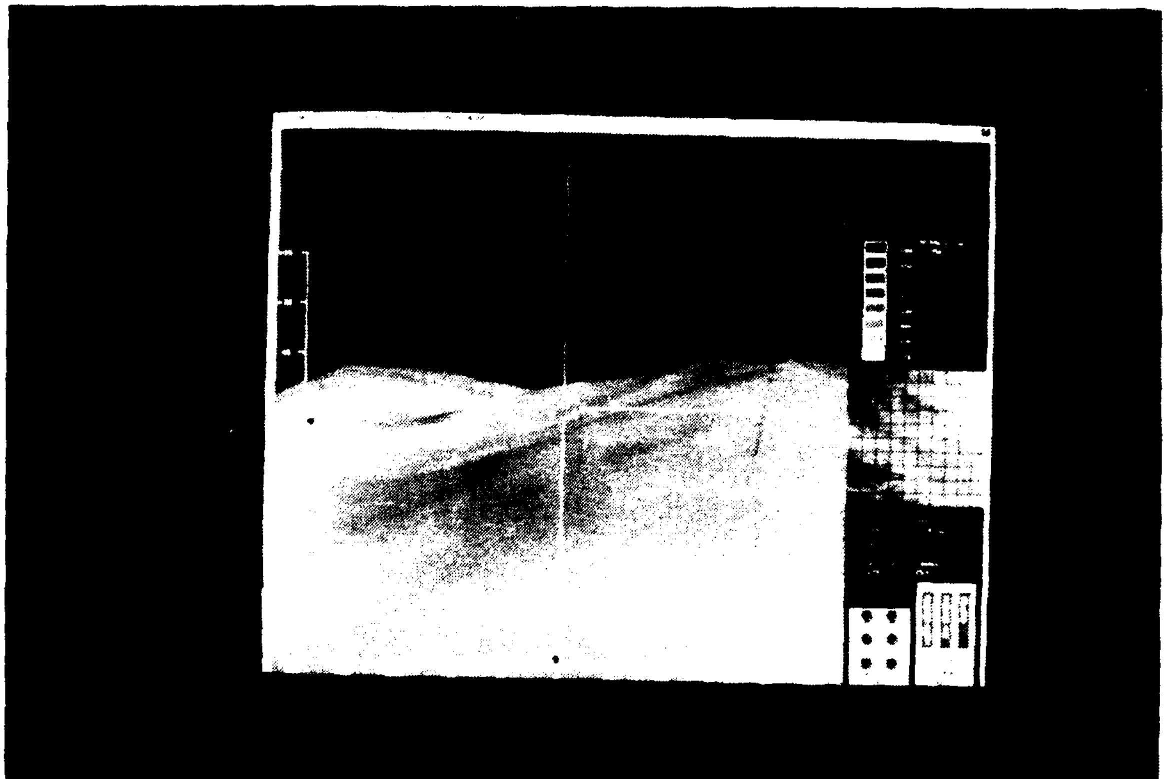

Figure 6.4 Mesh Display Using 100 Meter Resolution

TABLE 6.4 MPS PERFORMANCE MEASUREMENTS ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	969	8.00
ONE VEHICLE	15	840	8.00
NINE VEHICLES	55	1276	5.00
NINE VEHICLES	15	1128	6.00
MISSILE 1500m	90	1308	5.00
MISSILE 1500m	10	657	9.00

DISPLAYING DETAILED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	3907	2.00
ONE VEHICLE	15	1299	6.00
NINE VEHICLES	55	2955	4.00
NINE VEHICLES	15	1331	6.00
MISSILE 1500m	90	5748	2.00
MISSILE 1500m	10	982	7.00

on the IRIS 4D/120GTX are depicted in Table 6.4 through Table 6.7. Comparison graphs in Figure 6.5 and Figure 6.6 show the current simulators performance results as related to the manufacturer's specifications for the IRIS 4D/120GTX while drawing terrain in the *distance attenuated* or *detailed* terrain mode. The manufacturer's benchmark is a specification designed to produce the maximum number of polygons while performing few computations.

TABLE 6.5 MPS II PERFORMANCE MEASUREMENTS ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	971	11.53
ONE VEHICLE	15	843	10.56
NINE VEHICLES	55	988	9.15
NINE VEHICLES	15	857	9.57
MISSILE 1500m	90	1285	8.99
MISSILE 1500m	10	655	12.47

DISPLAYING DETAILED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	3912	3.82
ONE VEHICLE	15	1304	8.39
NINE VEHICLES	55	1553	7.01
NINE VEHICLES	15	859	9.86
MISSILE 1500m	90	5605	2.85
MISSILE 1500m	10	985	9.26

TABLE 6.6 MPS III PERFORMANCE MEASUREMENTS DRAWING POLYGON TERRAIN ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	935	7.10
ONE VEHICLE	15	836	7.81
NINE VEHICLES	55	986	7.34
NINE VEHICLES	15	824	7.53
MISSILE 1500m	90	1245	5.32
MISSILE 1500m	10	640	8.30

DISPLAYING DETAILED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	3830	2.31
ONE VEHICLE	15	1293	5.33
NINE VEHICLES	55	1462	5.41
NINE VEHICLES	15	824	8.04
MISSILE 1500m	90	5440	1.69
MISSILE 1500m	10	998	6.43

TABLE 6.7 MPS III PERFORMANCE MEASUREMENTS DRAWING MESH TERRAIN ON AN IRIS 4D/120GTX

DISPLAYING ATTENUATED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	935	11.26
ONE VEHICLE	15	841	11.05
NINE VEHICLES	55	995	9.08
NINE VEHICLES	15	833	9.35
MISSILE 1500m	90	1287	8.17
MISSILE 1500m	10	644	11.89

DISPLAYING DETAILED TERRAIN

PLATFORM	ZOOM ANGLE (DEGREES)	POLYGONS PER FRAME	FRAMES PER SECOND
ONE VEHICLE	55	3841	3.47
ONE VEHICLE	15	1295	8.52
NINE VEHICLES	55	1464	7.20
NINE VEHICLES	15	826	9.40
MISSILE 1500m	90	5834	2.64
MISSILE 1500m	10	998	8.62

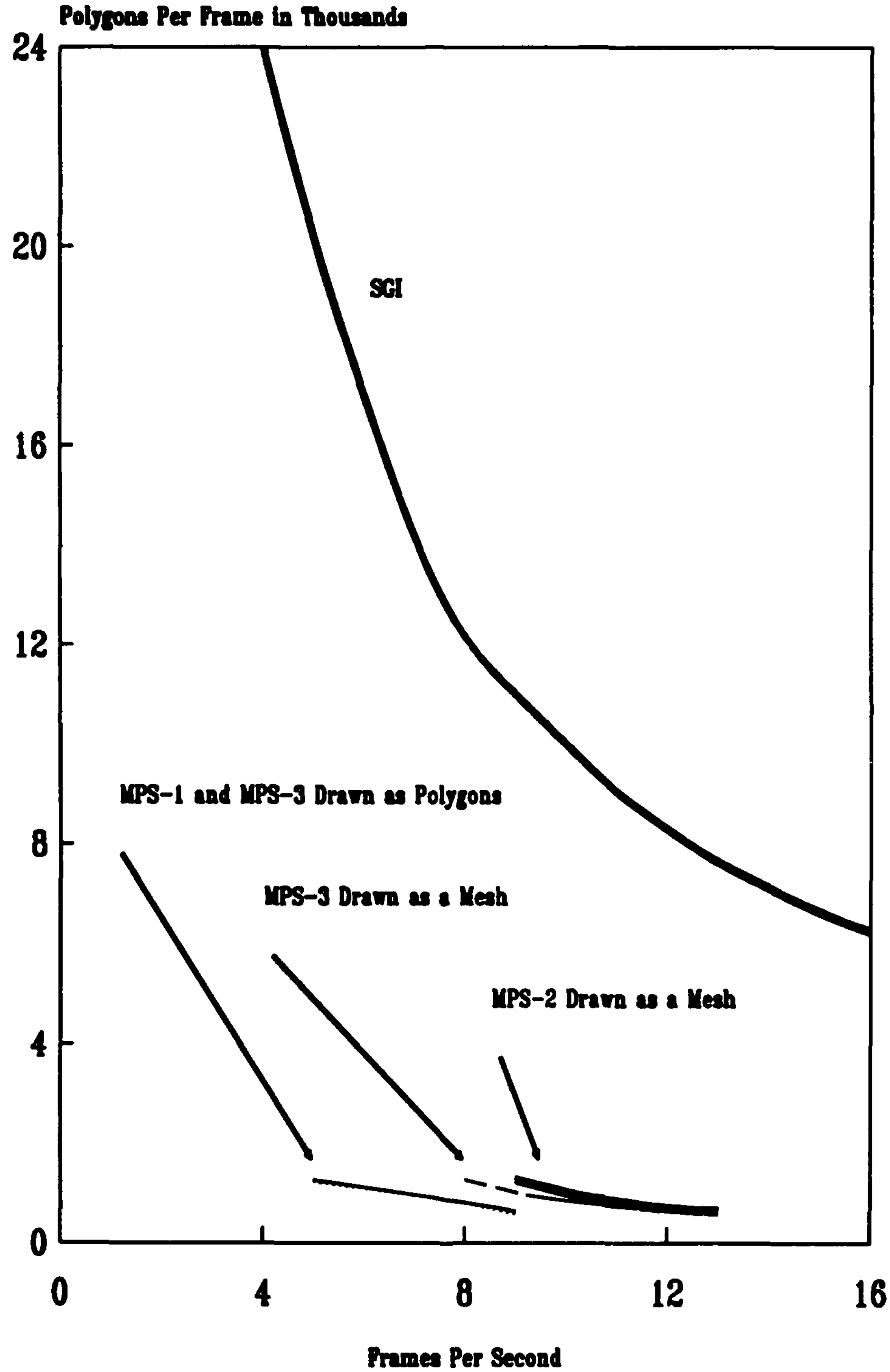

Figure 6.5 Expected and Measured Performance for the IRIS 4D/120GTX: Distance Attenuated Terrain

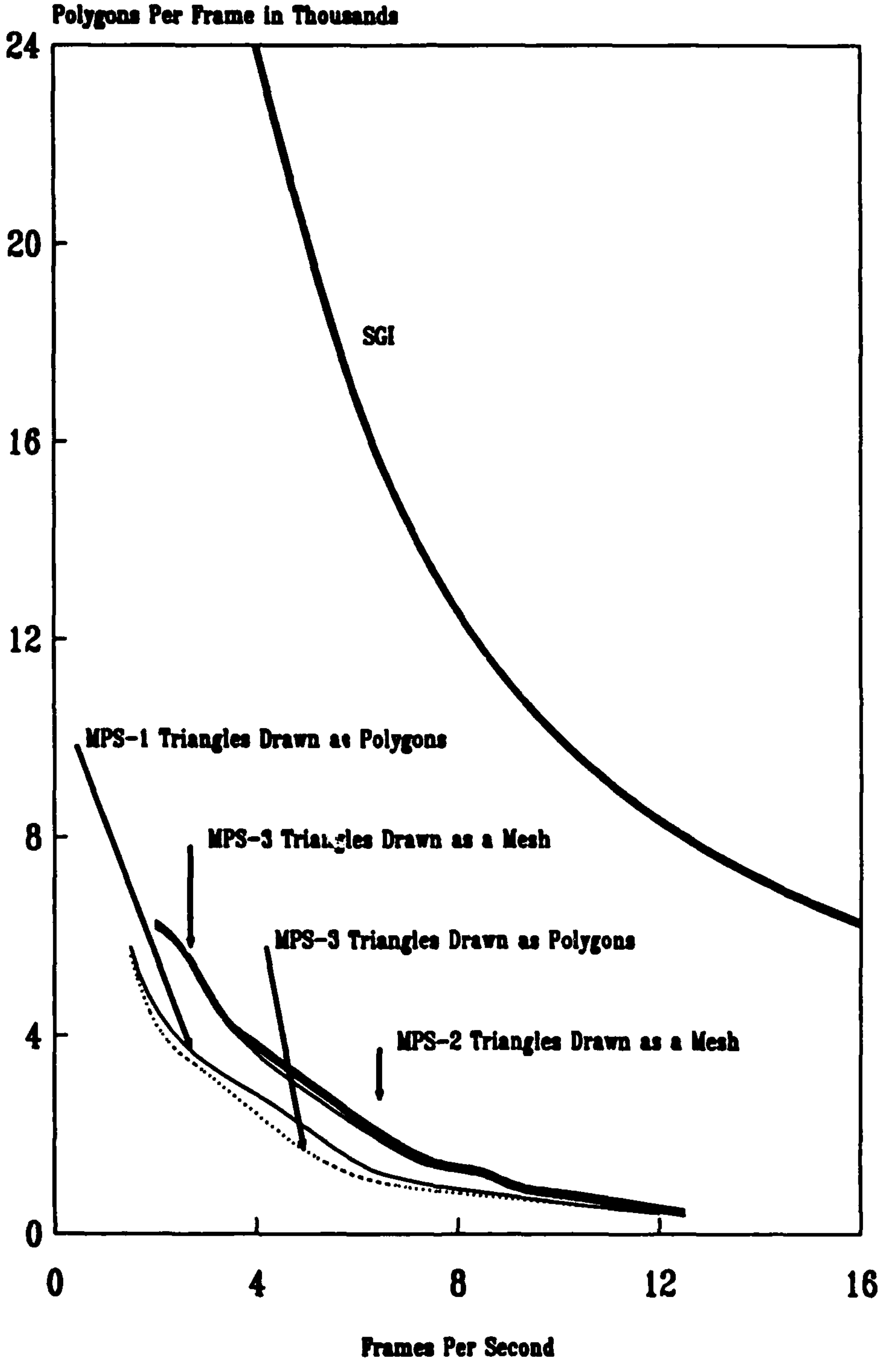

Figure 6.6 Expected and Measured Performance for the IRIS 4D/120GTX: Detailed Terrain

VII. SUMMARY

A. CONCLUSIONS

The objective of this work was to build an enhanced moving platform simulator that encompassed and improved upon the most desired features of simulators currently available at the Naval Postgraduate School. The result is the Moving Platform Simulator III. The simulator is capable of displaying DMA Level 1 DTED data and the special 12.5 meter resolution DMA data of Fort Hunter-Liggett, California. A major feature of the system is its ability to display high-resolution terrain in multiple intervals of resolution using either checkerboarded polygon or realistic mesh drawn terrain. The ability to toggle between the two terrain drawing methods makes the Moving Platform Simulator III an excellent tool for evaluating the performance capabilities of the Silicon Graphics, Inc., IRIS 4D/120GTX high-performance graphics workstation and its upgrades. In addition to creating the working model, performance tests were conducted using the newly combined features to establish a set of benchmarks for future evaluations of the system and new hardware.

B. FUTURE RESEARCH

1. Line of Sight Display

The robust features of the Moving Platform Simulator III allow for directed research in several areas. Since the base system for the simulator is MPS II, a natural

progression for the future would be to complete the work on line-of-sight calculations and displays. During the development of MPS III, considerations were given to ensure that the simulator would be compatible with previous research conducted.

2. SIMNET Integration

MPS systems at NPS have generated capabilities similar to and surpassing those of the SIMNET system. An extension of work on MPS III could be to adapt the system to utilize SIMNET databases and SIMNET networking protocols.

3. OFF File Conversion

The conversion of the system to the Object File Format (OFF) developed for use at NPS would enable the simulator to implement a larger and more realistic looking selection of vehicles and objects. Conversion of the system to object file format would eliminate many of the drawing routines and would allow for easier object modification and manipulation. To compliment this feature, object shadowing could be implemented.

4. Terrain Mobility

Currently vehicle operations are limited to the 10 km by 10 km grid area of the map on which they are originally placed. An algorithm should be developed that enables the vehicles to move smoothly over the entire database with no regard for artificial boundaries. Even though this would not be a very easy task, it should be given high priority in future modifications of MPS III.

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